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MECHANICAL PROPERTIES OF LUBRICANTS

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[Figures referred to herein are appended]

The study of the volumetric mechanical characteristics of lubricants is developing in the following main directions: (1) the study of the flow to friction points and behavior in different friction points; (2) the study of conditional mechanical characteristics (penetration number, etc.) with the aid of simple instruments in which, however, the simplest and most definite test conditions are not physically realized; (3) the study of elementary mechanical characteristics such as elasticity, viscosity, etc., which are found in the simplest and most physically accurate conditions possible; (4) the establishment of the relation between elementary and conditional mechanical characteristics of lubricants and their behavior in machines.

In the first direction, the greatest number of studies which merit attention concerns the study of the behavior of lubricants in roller bearings and the study of their viscous flow. Here the low-temperature characteristics of the lubricants are important. Also important are the low-temperature limit of their use and the change of viscous flow with the temperature and the moment needed for turning the journal in the bearing with a definite velocity. Another problem is the operating conditions of the lubricant in bearings at high temperatures at which the oil separates from the lubricant and the oxidation of the components causes scaling, etc. Much attention was devoted in the US to the study of low-temperature characteristics and high-temperature stability of lubricants, and standard test methods have been developed as a result of this.

Various conditional mechanical characteristics of lubricants have been suggested. The method of evaluating their consistency with the use of so-called penetrometers has received the most development. The results attained by studying the penetration numbers of lubricants are out of all proportion to the quantity of

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published works on this problem and the work expended on them. The only conditional mechanical characteristics which deserve attention are those which can be encountered in the study of the elementary characteristics of lubricants. In connection with this, the work of the Rebinder school is important. It has shown how the penetrometer should be modified to use it for studying the elementary mechanical characteristics of lubricants.

In studying the elementary mechanical characteristics of lubricants, basic attention was given to the determination of their viscosity and maximum shear stress. However, very little progress was made in these directions. It is sufficient to show that until recently the influence of temperature on the effective viscosity of lubricants was unknown. The elasticity characteristics of lubricants were neglected as well as the change from elastic deformation to plastic flows, etc.

Among the studies in which the connection between the mechanical characteristics of lubricants and their behavior at separate points and the flow towards them was studied, the effort of Velikovskiy to connect the effective viscosity of lubricants with their operation in an actual bearing is of the greatest interest. Research on modeling the processes occuring in various friction points, which was nonexistent until recently, is vital to the development of this most important trend in the study of the mechanical properties of lubricants.

It is scarcely necessary to point out that the study of the behavior of lubricants in friction joints of machines should be based on their elementary mechanical characteristics, to which reference is now made. Within the limits of one paper, only the main trends and prospects of the experimental study of these characteristics can be stressed.

Elasticity Characteristics of Lubricants

The difficulty of studying elastic lubricants is: (1) the absolute values of the dimensions of the (reversible) deformation are very small; (2) it is particularly difficult to work with such sheer stresses, when the lubricants behave, at first glance, as ideally elastic bodies whose deformation is not dependent on the time of the action of the load.

Considering these difficulties, it was necessary to develop a method of studying the elastic characteristics of lubricants which would allow an uninterrupted, automatic registration of small dimensions of deformation at changing and constant stresses and temperatures. The apparatus comprised a brass cylinder, by means of which it was possible to study the kinetic, elastic and plastic deformation of lubricants. A cylindrical core on an elastic thread was suspended in it. A constant or alternating moment could be applied to the elastic thread thus inducing a shear stress τ on the surface of the core. The lubricant was put into the cylinder flush with its edge, so that the case of simple shear in the cylindrical ring was realized. A small mirror was fitted in the upper part of the core, and the beam of light reflected by it was photographically recorded on a rotating drum. The apparatus could be maintained at various temperatures by means of a thermostat.

The elastic characteristics of various lubricants were studied, more specifically greases, since this is the most common type of lubricant. On the other hand, their elastic characteristics are less well defined than, for example, "konstalin." Consequently, they are more difficult objects of study.

The grease was especially prepared on an industrial scale from a Dossur distillate ($\nu_{20^\circ} = 90$; $\nu_{37.8^\circ} = 34$; $\nu_{98.9^\circ} = 5$ centistokes), solidified 14.2 percent by weight of Ca-soaps obtained by saponification of cottonseed oil with a fatty acid number of 185. The grease contained 2 percent water, 0.6 percent nonsaponified oil and had a free acidity of 0.6 percent as compared with oleic acid.

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The hot grease (70 - 80 degrees C) was poured into the apparatus in which it remained at room temperature for 14 to 16 hours. After this the kinetics of its deformation were studied. One of the photograms obtained is shown in Figure 1, where the abscissa is the time and the ordinate, the rotation of the core (expressed in angles of turn of the core which was immersed in the lubricant and suspended on the elastic thread).

With reference to Figure 1, at t = 0, there was applied a shear stress of τ = 5.75 g/sq cm. At point B, the load was removed. Similarly in points O_1, O_2, O_3 shear stresses equal to 6.90; 8.05; 9.20 g/sq cm were applied. Sections O_1A_1, B_1C_1, etc., correspond to elastic deformations which occur so fast that no trace is left on the photographic paper. These elastic deformations are directly proportional to the shear stress. It is very important that they have the same size when removed as when applied. By using the photogram (Figure 1), the stress modulus can be calculated for the grease, which at 10 degrees C is equal to 8.4 x 10-3 kg/sq mm.

From an examination of the photogram, it is also clear that lines AB, A_1B_1,..., CO_1, C_1O_2, are not horizontal straight lines. Their inclination increases steadily with the growth of the shear stress; the deformations of the grease, even though they alter at a constant stress, nevertheless remain reversible after the removal of the load.

The curves AB, A_1B_1, CO_1, C_1O_2,..., correspond to the effect of the elastic reaction in the grease. Lines AB, A_1B_1,..., are called direct reactions, which, according to Bingham's supposition, also have elastic pre-effects. Lines CO_1, C_1O_2,..., are called reverse reactions or simply reactions.

The phenomena of elastic reaction (also called reverse creep) were discovered more than a hundred years ago by Weber while studying silk threads. Since then they have been chiefly studied in metals where these phenomena have an important technical significance. This is, apparently, the first attempt to describe elastic reactions and creep of lubricants, although they are verymarked and essential for understanding the elastic characteristics.

In small shear stresses shown above, the greases, even though they do not conduct themselves as ideally elastic bodies, to use Byurgers' terminology, are completely elastic solid bodies, since their deformation is in time reversible. Other bodies are known, in particular high polymers, some of which have similar characteristics.

At higher stresses, the pre-effect and elastic reaction is considerably increased, as is clear from the photogram (Figure 2) which is an extension of the photogram (Figure 1). As the stresses increase, the nonreversible residual deformation also increases steadily. At fairly high stresses the process of flow begins.

Curves $O_7A_7B_7$ (Figure 2), taken at a constant shear stress "τ" = 18.4 g/sq cm, are of particular interest.

Elastic deformation takes place simultaneously with the application of the load on which the pre-effect is rapidly superimposed, due to which the steeply rising curve inclines to the right. However later, the steepness of the curve A_7B_7 again increases, so that there is a point on it. The steeply rising upper part of the curve A_7B_7 corresponds to the relatively rapid flow of the grease.

At the point B_7 the load was removed from the grease. The motion of the curve of the elastic reaction (B_7C_7D) shows that: (1) on the curve $O_7A_7B_7$, the process of nonreversible plastic flow takes place, leading to the appearance of nonreversible, residual deformation; (2) immediately after the removal of the stress, the layer of grease in which plastic flow was taking place, becomes a means of transmitting elastic deformation, i.e. its structure can be restored fairly quickly. The elastic reaction appearing on the curve B_7C_7D is explained most simply by the fact that plastic flow is intensively developed only in the layer immediately adjoining the core where the greatest shear stress is acting.

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The residual mass of the grease is in an elastically strained condition. After removing the stress, the reaction process takes place in it, during which the accumulated elastic energy brings about the rotation of the core of the torsion elastic gage.

The mechanical properties of the bodies can be illustrated with the aid of a simplification of the kinetic system of the mechanisms, consisting of ideally elastic springs, slides which have a finite coefficient of external friction, and pistons which move in the viscous fluid. It can be substantiated on the basis of experimental data that the mechanical characteristics of greases at moderate stresses are qualitatively illustrated by the system shown by Figure 3. In this system, the parallel elements A_2 and B_1 move so that their stems always remain horizontal.

Sections of the lines BC, $O_1A_1, C_1, \ldots$, (Figure 1) correspond to the deformation of the spring A_1 (Figure 3). The motion of piston B_1 and deformation of the spring A correspond to the curves showing the pre-effect and reaction on Figure 1. Whence it also follows that the numerical values of the shear modulus of the grease given above agree with the modulus of elasticity of the spring A_1.

The slide C, having a static coefficient of friction, indicates the presence of the maximum shear stress (τ_{Max}) in the grease. The slide moves when $\tau > \tau$ Max. Its movement is connected with the displacement of the piston B_2 in the viscous fluid. Gradual displacement of the piston B_2 corresponds to the process of nonreversible plastic flow of the lubricant.

When using the kinematic system, special attention must be made to the presence of an S-bend in the curve $O_2A_2B_2$ (Figure 2). This indicates the value produced by the combination of the shear stress and deformation for plastic flow.

When the apparatus is charged with grease, by putting it in the glass in which the cone on the elastic thread is immersed, the kinetics of grease deformation is distinguished quantitatively and qualitatively from the above description. This fact corresponds very well to the effect which was found by Segalov in the Rebinder laboratory in working with a cone submerged in the lubricant. On Figure 4 the upper part is the photogram of the kinetics of grease deformation, tested by the method described above. The lower part is the photogram of the grease of the same composition, which was obtained by the usual method of mixing and pouring into the apparatus after a day of complete cooling. In both examples, the kinetic deformation was studied at the same shear stress. From a comparison of the photograms of Figure 5, it follows that: (1) for the second example, the pre-effect and reaction are much more sharply expressed; (2) in a mixed grease, the abrupt change from the ideally elastic deformations in solid-viscous deformation, characteristic for Kelvin bodies is absent (the parallel combined spring and piston in the viscous fluid), which is possibly connected with the decrease of resistance of the element B_1 indicated on Figure 3; and (3) at small shear stresses in both cases, nonreversible residual deformation is absent.

In studying the elastic characteristics of lubricants, it is very important to determine the sizes of the nonreversible deformations. The difficulty here is connected with the presence of the process of elastic reaction. Its speed is gradually decreased so that it is entirely completed only after very long periods of time. As a result of this, residual deformation at any given time is composed of reversible (in time) and nonreversible deformation.

Acceleration of the process of elastic reaction and its practical completion can be attained by increasing the temperature of the lubricant 10 to 20 degrees. This makes it possible to establish approximate values of the nonreversible residual deformation in short periods of time. This is illustrated by the photogram (Figure 5). In the moment t = 0, the shear stress τ = 2.30 g/sq cm was applied.

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At the point A it was increased to τ = 8.05 g/sq cm; the rapidly occurring shear, which corresponds to the line AB, is composed of elastic deformation and nonreversible plastic deformation, which can thus be imposed on one another; at the point B, the load was removed; BC is the curve of elastic reaction; at the point C the temperature of the oil was increased by 10 degrees. From the subsequent course of the curve of elastic reaction (line CD), one can see its acceleration due to increasing the temperatures, so that at point D, the decrease of the residual deformation has practically stopped and the line HF is horizontal.

When heating oils to speed up the occurrence of elastic reaction, it is important to note that alternate heating and cooling of greases even at temperatures far from their boiling temperatures, leads to a hardening of their structures.

The importance of the problems examined in the present section depends mainly on the fact that the possibility of studying lubricants as elastic-solid bodies has been demonstrated. From this it follows, that the methods of investigating them at relatively low shear stresses, and the phenomena to be expected, are predetermined, to a considerable extent, by facts already known from the study of the deformations of solid bodies; in particular, from the mechanical properties of polycrystalline metals and the higher fibrous polymers.

[Appended figures follow.]

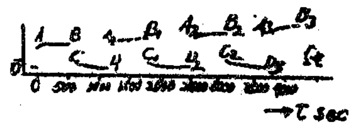

Figure 1. Kinetics of the Elastic Deformations of Greases.

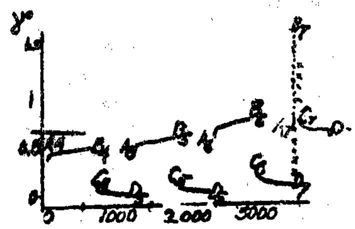

Figure 2. Kinetics of Elastic and Elastic-plastic Deformations of Greases

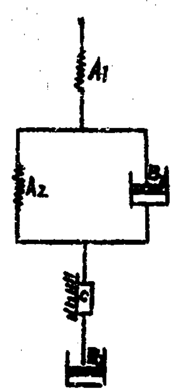

Figure 3. Simplifications of the Kinematic System, Illustrating the Deformation of Greases at Small Stresses.

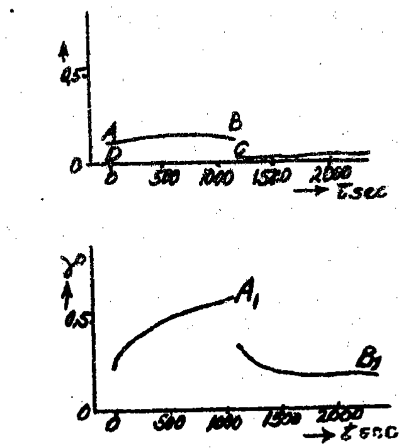

Figure 4. Influence of Mixing the Greases on the Kinetics of their Elastic Deformations.

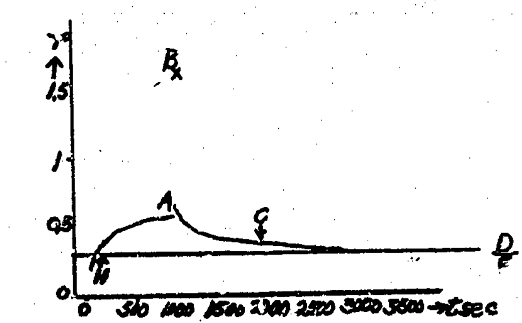

Figure 5. Influence of Heating on the Kinetics of the Elastic Reaction in a Grease.

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